CRUSTACEAN ZOOPLANKTON COMMUNITIES OF ACIDIC, METAL-CONTAMINATED LAKES NEAR SUDBURY, ONTARIO

TECHNICAL REPORT LTS 79-4

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Ministry of the Environment
Ontario

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PREFACE

The Ontario Ministry of the Environment in cooperation with the Ontario Ministry of Natural Resources began a comprehensive investigative program in the Sudbury area in 1973 called the Sudbury Environmental Study (S.E.S.). The formal program was initiated in response to earlier studies and reports documenting environmental damage apparently due to smelting operations in Sudbury. Studies include quantification of industrial emissions, atmospheric transformations and transport of those emissions, deposition measurements, determination of chemical and biological lake water quality, developing methods to reclaim acidified lakes and evaluating fisheries in key study lakes. Most of the projects are conducted concurrently by the Air Resources, Water Resources and Laboratory Services Branches of the Ministry of the Environment and by Regional Ministry of the Environment and Ministry of Natural Resources staff.

The Limnology and Toxicity Section of the Water Resources Branch has been primarily responsible for quantitatively describing the chemistry and biology of very acidic ($pH<4.6$) lakes, developing methods for ameliorating stress associated with low pH and nutrient concentrations and high heavy metal concentrations, and measuring the toxicity of lake waters, before and after chemical manipulations, to fish.

Clearwater Lake has been maintained as a contaminated "control" lake since 1973. Its chemistry and phytoplankton assemblages have been previously described. In this report the crustacean zooplankton community of the lake and its interaction with the lake's phytoplankton community are described.

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INTRODUCTION

Studies conducted in different parts of the world have demonstrated that although the biomasses of phytoplankton communities of acidic lakes with (Yan 1979) or without (Almer et al. 1978) associated heavy metal problems are no lower than those of non-acidic lakes with similar concentrations of phosphorus, the structure of the phytoplankton communities of acidic lakes is quite different from that of non-acidic lakes. Recently, several regional surveys of the zooplankton of lakes acidified by the atmospheric deposition of strong acids have been conducted. While these have demonstrated that the diversity of zooplankton communities is reduced by acidification (Hendrey et al. 1976, Almer et al. 1978, Leivestad et al. 1976, Roff and Kwiatkowski 1977), and that point-in-time community structure of acidic and non-acidic lakes differ (Sprules 1975), the available information on the seasonal variability (Roff and Kwiatkowski 1977) and the biomass (Bible 1972) of zooplankton populations in acidic lakes is unfortunately very limited. Studies designed to investigate the interaction of phytoplankton and zooplankton communities in acidic lakes have not been performed, although it is known that herbivorous zooplankton can directly affect the standing stock and structure of phytoplankton communities (Shapiro 1978, Anderson et al. 1978, Hrbáček et al. 1961). Therefore, it can not yet be ascertained if the changes in the phytoplankton communities that do occur in acidic lakes might, to any extent, be attributable to changes in zooplankton communities.

Lakes near Sudbury, Ontario that are acidic and contaminated with heavy metals have been investigated for many years (Gorham and Gordon 1960, Beamish and Harvey 1972, Dillon et al. 1979). Since 1973, we have been studying Clearwater Lake and three other lakes (Middle, Hannah and Lohi) that have been acidic (pH 4.1-4.6) and contaminated with Cu and Ni for between twenty and eighty years. We have studied Nelson Lake, a lake at an earlier stage of acidification (pH ≃5.6) since 1975. While the chemistry of the latter four lakes has been manipulated by experimental additions of neutralizing or fertilizing substances (summarized in Dillon et al. 1979) we have not adjusted the chemistry of Clearwater Lake. Since 1976 we have also been studying six lakes with low alkalinities in the Haliburton District of south central Ontario.

Six years of zooplankton data from Clearwater Lake are presented in this paper and compared with pre-manipulation data from Nelson Lake, the other acidic lakes near Sudbury and the non-acidic lakes in Haliburton. The objectives of this paper are:

1. To describe seasonal and annual variations in the biomass and community composition of the crustacean zooplankton community of Clearwater Lake.

2. To construct preliminary hypotheses concerning ways in which acidification of lakes influences typical interactions between phytoplankton and zooplankton at the level of the community

METHODS

Scheider et al. (1975) and Yan (1979) have described the methods employed for the collection and analysis of chemical and phytoplankton samples, respectively.

From 1973 to 1975, zooplankton in Clearwater, Middle, Lohi and Hannah Lakes were collected with an unmetred, Wisconsin net (11 cm diameter, 80μ mesh) which was towed vertically from one metre above the sediment surface to the surface at the deepest location in each lake. From 1976 and onward samples were taken using a 34ℓ, self-closing, plastic trap (Schindler 1969) at 2-3m intervals to one metre above the sediment surface in the Sudbury and Haliburton lakes. Except for a short period in 1977 in which 40μ mesh was used in Clearwater Lake, the trap's attached net and bucket was equipped with 80μ mesh. Trap samples were taken at four pelagic stations in the Sudbury lakes (collections from the same depths from different stations were subsequently combined) and at the deepest location only in the Haliburton lakes. All samples were preserved in the field with a neutralized, sugar-formalin solution (Haney and Hall 1973). Sampling periods are indicated in Table 1.

In the laboratory, trap samples were transferred to graduated cylinders, made up to 100 ml with tap water and mixed by bubbling with air. Using a wide-mouth pipette, a fraction of each sample which was proportional to the volume of the lake stratum from which the sample had been taken, was removed. These fractions were pooled to provide a single morphometrically-weighted sample assumed to be representative of the whole lake.

Table 1: Latitude, longitude, lake surface area (A_O), mean depth ($\bar{z}$), and dates for which zooplankton data are reported (sampling period) for the study lakes.

Lake	Latitude (°N)	Longitude (°W)	A_O (ha)	$\bar{z}$ (m)	Sampling Period[1]
Clearwater	46° 22'	81° 03'	72	8.1	Aug.-Nov. 1973 May-Oct.(Nov.) 1974-78
Hannah	46° 26'	81° 02'	21	4.0	Aug.-Nov. 1973 May-Nov. 1974
Lohi	46° 23'	81° 06'	40	6.2	Aug.-Nov. 1973
Middle	46° 23'	81° 06'	30	6.2	July-Nov. 1973
Nelson	46° 44'	81° 05'	309	11.6	May-Oct. 1975, 1976
Blue Chalk	45° 12'	78° 56'	49	8.5	May-Nov. 1977
Red Chalk	45° 11'	78° 56'	44	16.7	May-Nov. 1977
Harp	45° 23'	79° 08'	67	12.4	May-Nov. 1977
Jerry	45° 23'	79° 06'	50	12.4	May-Nov. 1977
Chub	45° 13'	78° 59'	32	8.8	May- Nov. 1977
Dickie	45° 09'	79° 05'	93	4.9	May-Nov. 1977

[1] Clearwater, Hannah, Lohi, Middle and Nelson Lakes were sampled bi-weekly. The remaining lakes were sampled weekly.

The monographs routinely used for purposes of identification were those of Edmonson (1959) and Brooks (1959). No attempt was made to speciate nauplii. Calanoid and cyclopoid copepodids were separately identified but not speciated. All crustacean zooplankters were enumerated if the sample contained <200 individuals, otherwise at least 200 individuals were enumerated.

The mean annual biomass of all dominant zooplankters was determined for each lake. To do this fifty to three hundred individuals (depending on their size) were chosen to equally represent all size classes observed in a year. These were removed from the samples, rinsed four times with distilled water to remove adhering preservative, placed on preweighed coverslips, dried to constant weight (≈24 hours) at 80^{o}C and weighed to the nearest μg on a Sartorius electrobalance. Separate dry weights were obtained for naupliar, copepodid and adult copepods, (weights of individual species available from the authors upon request).

Counts of dominant zooplankters in each lake in each year were converted to biomass using the measured weights. Where possible, individual weights of less common species were taken from other years or other study lakes. Because they were not sufficiently common to measure weights in our study lakes, the mean dry weight of *Epischura lacustris* was taken from Thompson Lake (Strus, unpub. data) and weights of *Simocephalus sp., Ceriodaphnia megalops* and *Polyphemus pediculus* were obtained from other collections (J. Cooley, pers. comm.).

Ice-free period averages of biomass or community composition were corrected for any differences in sampling frequency by generating monthly averages and averaging the monthly means.

DESCRIPTION OF THE STUDY AREA

The location and selected aspects of the morphometry of the study lakes are summarized in Table 1. Dillon et al. (1979) have summarized the chemistry of Clearwater, Middle, Lohi and Hannah Lakes. The chemistry, phytoplankton and experimental manipulations of Nelson Lake are summarized by Yan et al. (1977). Selected aspects (pH, SO_4, Al, Mn, alkalinity) of the chemistry of the Haliburton Lakes have been previously tabulated

(Dillon et al. 1978, Scheider et al. 1979). Yan (1979) and Nicholls (in preparation) summarized phytoplankton data for the study lakes.

The study lakes are all clear (annual mean Secchi depths 6-11m in the Sudbury lakes and 3-7m for the Haliburton lakes). Temperature regimes are related to lake morphometry (Table 1). Blue Chalk, Red Chalk, Harp, Jerry, Chub and Nelson Lakes are first-class dimictic[1] lakes. Dickie, Clearwater, Lohi and Middle Lakes are second-class dimictic lakes, and Hannah Lake, the shallowest of the lakes is third-class dimictic.

All, excepting Dickie Lake, are oligotrophic (0.5-3.0 μg chlor a L^{-1} for the Sudbury lakes and 2.0-6.0 μg chlor a L^{-1} for the Haliburton lakes). Total N:Total P ratios are generally 20 to 50 indicating that phosphorus is the nutrient present in shortest supply (Schindler 1977).

Unusually large atmospheric loadings of heavy metals (Jeffries and Snyder 1979) have resulted in elevated concentrations of Cu and Ni in the Sudbury lakes. Substitution of H^+ from precipitation for cations in the overburden of the watersheds during runoff has resulted in elevated levels of Ca, Mg, Al and Mn (Dillon et al. 1979). Al and Mn concentrations are elevated in other acidic lakes in Ontario more remote from Sudbury (Beamish and Van Loon 1977, Scheider et al. 1979). Elevated levels of Cu and Ni exist only in lakes within about 70 km of Sudbury (Dillon et al. 1979).

The Sudbury study lakes that are acidic, have been so for at least two decades. While the Haliburton lakes are not acidic, their buffering capacities are very low and precipitation in the area is very acidic (Dillon et al. 1978). In consequence, the pH's of surface water of the lakes with the lowest alkalinities (Chub and Dickie) are depressed to 5.0 for a short time in early spring (Jeffries et al. 1979).

All of the study lakes are situated in the Precambrian Shield, an area that in terms of crustacean zooplankton communities, may be considered a single zoogeographic region (Patalas 1971, Sprules 1975). Within this region, Patalas (1971) identified four community types related to lake morphometry. All of the study lakes, excepting Nelson Lake, fall within Patalas' Type II category, those of intermediate size and depth. Nelson Lake fits the larger and deeper Type I category. Both these categories, however, are characterized by zooplankton communities dominated by *Cyclops bicuspidatus thomasi* and *Diaptomus minutus* (Patalas, 1971).

[1]Definitions of classes of dimictic lakes are from Hutchinson (1957, p.439-440).

Table 2: Comparison of selected crustacean zooplankton data from net (1973-1975) and trap (1976-1978) collections from Clearwater Lake. Data summarized are from August and onward of each year and except where otherwise indicated are averages.

Parameters	Net 1973	Net 1974	Net 1975	Trap 1976	Trap 1977	Trap 1978
Numbers						
No. of species collection^{-1}	3.6	4.1	4.0	3.5	4.3	3.7
No. of organisms L^{-1}	7	25	4	14	24	15
Maximum No. of adults L^{-1}	21	39	4	28	54	26
No. of *B. longirostris* (% of adults)	96	99	99	99	99	97
Biomass						
Total crustacea (mg m^{-3})	5.0	19.2	3.3	11.2	17.1	9.4
Cladocera (% of crustacea)	90	98	78	90	98	94
B. longirostris (% of crustacea)	89	97	77	89	96	87

RESULTS AND DISCUSSION

1. Net vs Trap Collections

Several investigators have demonstrated that unmetred tow nets underestimate standing stocks, especially that of species with more highly developed avoidance mechanisms (Schindler 1969, Pedersen *et al.* 1976). When data from trap and net collections from Clearwater Lake were compared (Table 2), no significant bias ($\rho > 0.01$, one way ANOVA with sampling gear as treatments, ice-free period averaged data as observations) attributable to sampling gear was detected for any of the community parameters which were compared. We conclude that for Clearwater Lake, average annual estimates of community parameters were adequately derived from net collections. This conclusion must be regarded as being applicable to only the acidic Sudbury lakes, unless tested and found applicable elsewhere.

2. Non-acidic Lakes

Zooplankton communities of the Haliburton Lakes will be described in detail elsewhere (Strus, in prep.). Selected summary data only are presented in this report.

An average of between seven and fifteen species of zooplankton were identified in each sample in the non-acidic lakes (Table 3). This compares favourable with the 10.4 species lake^{-1} identified by Sprules (1975) in non-acidic, soft water lakes in the La Cloche Mountain region of Ontario. Total crustacean biomass varied between 26 and 86 mg m^{-3} but among the oligotrophic lakes (excluding Dickie Lake), biomasses were quite comparable (26-49 mg m^{-3}). Although important, cladocerans generally contributed less to total biomass than copepods. The contribution of *Bosmina longirostris* to total biomass was insignificant (Table 3) although the species was identified in approximately 90% of the samples.

The biomasses and relative contribution of cladocerans and copepods to total biomass were quite similar to those of non-acidic, oligotrophic lakes in northwestern Ontario, the U.S.A. and Italy for which ice-free period average data could be generated (Table 3).

Table 3: A summary of selected zooplankton and chemical data from the study lakes. Data from other lakes are presented for comparison. Values are averaged for the ice-free period unless otherwise stated.

Lake		Source	Collection Method	pH	[TP] µg L^{-1}	[Cu] µg L^{-1}	[Ni] µg L^{-1}	No. of Species Collection^{-1}	Crustacean Biomass				Lake Type
									Total mg m^{-3}	% Crustacea			
										Copepoda	Cladocera	*B. longirostris*	
Acidic Study Lakes													
Clearwater	1973	This Study	Net	4.3	5	90	270	3.6	5.0	10	90	89	Oligotrophic
	1974	"	"	4.2	5	97	290	3.4	13.3	4	96	95	"
	1975	"	"	4.3	3	110	270	3.9	4.3	8	92	90	"
	1976	"	34L trap	4.2	5	92	270	3.5	8.4	16	84	83	"
	1977	"	"	4.1	7	81	280	3.9	13.8	6	94	93	"
	1978	"	"	4.4	5	74	260	3.6	6.5	20	80	79	"
Hannah	1973	"	Net	4.4	8	1080	1600	2.9	0.68	29	71	60	"
	1974	"	"	4.3	5	1110	1890	3.1	0.71	56	44	33	"
Middle	1973	"	"	4.5	7	500	1060	3.4	13.7	8	92	92	"
Lohi	1973	"	"	4.6	6	83	250	3.6	24.0	19	81	80	"
Non-Acidic Study Lakes													
Nelson	1975		34L trap	5.7	5	22	16	8.0	34.0	96	4	2	"
	1976	"	"	6.5	5	13	10	7.0	35.1	84	16	14	"
Blue Chalk	1977	This Study	"	6.6	8	<2	<2	11.9	48.8	64	36	0.3	"
Red Chalk	1977	"	"	6.4	6	<2	<2	14.6	31.0	69	31	0.6	"
Harp	1977	"	"	6.4	8	<2	<2	12.5	31.5	44	56	2.7	"
Jerry	1977	"	"	6.4	10	<2	<2	9.3	26.0	79	21	0.3	"
Chub	1977	"	"	5.7	10	<2	<2	11.0	48.6	75	25	0.1	"
Dickie	1977	"	"	6.0	13	<2	<2	10.3	85.7	36	64	0.06	Oligo/meso

Table 3: Cont'd.....

Lake	Source	Collection Method	pH	[TP] $\mu g\ L^{-1}$	[Cu] $\mu g\ L^{-1}$	[Ni] $\mu g\ L^{-1}$	No. of Species Collection^{-1}	Crustacean Biomass: Total $mg\ m^{-3}$	% Crustacea: Copepoda	% Crustacea: Cladocera	% Crustacea: *B. longirostris*	Lake Type
Other Lakes												
122	Schindler and Novén 1971	29L trap	6.5[1]	13, 3[2]	-	-	8[3]	81	61	39	-	Oligo/meso
132	"	"	6.9[1]	8, 7[2]	-	-	9[3]	169	37	63	-	"
Findlay	Pederson et al. 1976	Net	-	10.3	-	-	-	25[5]	59	41	-	Oligotrophic
Chester Morse	"	"	-	17.2	-	-	-	20[5]	53	47	-	"
Sammamish	"	"	-	23.4	-	-	-	52[5]	72	28	-	Mesotrophic
Maggiore	Ravera 1969	"	7.5-8.9[4]	-	-	-	-	27	85	15	-	Oligotrophic

[1] From Schindler (1972)

[2] Values are spring and midsummer TDP, respectively.

[3] From single net haul (Patalas 1971)

[4] From Giussani et al. (1976)

[5] Not corrected for filtering efficiency of nets.

3. Acidic Lakes

a) Occurrence of Species

Seventy-nine zooplankton samples from Clearwater Lake were examined. These had an average of 3.7 species sample^{-1}, an average that was much less than in the non-acidic lakes (Table 3). Ninety percent of the collections had between three and five species, suggesting that the average number of species that exist at any point in time in acidic lakes may be accurately estimated from a small number of samples. Sprules (1975) observed a quite comparable average of 3.64 species collection^{-1} in 28 La Cloche Mountain Lakes that were not contaminated with Cu or Ni but had pH levels of 3.8 to 5.0.

The average number of species collection^{-1} observed in Middle and Lohi Lakes was quite comparable to that of Clearwater Lake, but somewhat fewer species were identified in each sample in Hannah Lake, the lake with the highest metal levels (Table 3).

A total of thirteen species of crustacean zooplankton were identified in Clearwater Lake collections. Four were observed once only, and only three species (*B. longirostris, Chydorus sphaericus* and *Cyclops vernalis*) were present in all years (Table 4). *B. longirostris* was dominant, as defined by Patalas (1971) in all samples and *C. vernalis* was often codominant in the early spring. This pattern of dominance is quite different from what Patalas (1971) observed for morphometrically similar, non-acidic lakes in northwestern Ontario.

B. longirostris is the most widely distributed cladoceran in Ontario, occurring in 45% of the 244 lakes surveyed by Brandlova et al. (1972). It is commonly identified and often a dominant zooplankter in acidic environments (Carter 1971, De Costa 1975). *C. sphaericus* and *C. vernalis* have been recorded in ponds with pH levels as low as 3.4 and 4.4, respectively (Lowndes 1952).

Almer et al. (1978) and Sprules (1975) have noted that acidic lakes are characterized by a scarcity of species of *Daphnia*, a taxon which, in addition suffers reproductive impairment (Biesinger and Christensen 1974) at copper and nickel concentrations lower than those of Clearwater Lake (Table 3). No species of *Daphnia* were observed in Clearwater Lake collections.

Table 4: Clearwater Lake zooplankton species, 1973-1978. Years and proportion of collections (Rel. Freq.) in which species were observed are indicated. "+" indicates observation in only one sample.

Species	Years	Rel. Freq. %
Cyclops vernalis Fisher	1973-1978	81
C. bicuspidates thomassii Forbes	1974, 1977	9
Diaptomus minutus Lilljeborg	1977, 1978	4
Epischura lacustris Forbes		+
Bosmina longirostris (O.F. Müller)	1973-1978	99
Chydorus sphaericus (O.F. Müller)	1973-1978	91
Ceriodaphnia megalops Sars	1973, 1974	28
Simocephalus serrulatus (Koch)	1975-1978	18
Polyphemus pediculus (L.)	1975-1978	7
Acantholeberis curvirostris (O.F. Müller)	1973, 1974	3
Eubosmina sp.		+
Macrothrix laticornis (Jurine)		+
Alona affinis (Leydig)		+

Sprules observed that the common dominants of acidic lakes in the La Cloche Mountains were *Diaptomus minutus*, a species infrequently observed in Clearwater Lake (Table 4), *Bosmina sp.* (most probably, *longirostris*) and less commonly *Holopedium gibberum*. Neither Sprules nor Roff and Kwiatkowski (1977) identified *C. sphaericus* or *C. vernalis* in these lakes, although the species are quite common, though never dominant in northern Ontario lakes (Patalas 1971).

Yan (1979) observed that the phytoplankton community of Clearwater Lake resembled that of other acidic lakes in Ontario and Scandinavia despite its contamination with Cu and Ni. Although there are similarities in the relative occurrence of zooplankton species between Clearwater Lake and acidic lakes in Ontario that are not contaminated with Cu and Ni (scarcity of *Daphnia*, importance of *B. longirostris*), the importance of *C. sphaericus* and *C. vernalis* and the scarcity of *D. minutus* suggests that the contamination of Clearwater Lake with Cu and Ni has resulted in a species composition that is somewhat atypical of acidic lakes in Ontario.

b. Biomass

The average biomass of the zooplankton community of Clearwater Lake varied between 4.3 and 13.8 mg m^{-3} in the ice-free period, and was significantly lower (ρ <0.01 t-test of difference between means) than that of the non-acidic study lakes (Table 3). Cladocerans were much more important contributors to biomass than were copepods in the acidic lakes. *B. longirostris* comprised >95% of the cladoceran biomass in each year in Clearwater Lake (Table 3), and virtually all of the community biomass from June to August (Fig. 1).

Densities of *C. vernalis* were at a maximum in May and June soon after vernal overturn (Fig. 2) although there was occasionally a second smaller peak in the fall (Fig. 1). *B. longirostris* has generally been observed to be dicyclic in nutrient-rich (Haney 1973) or nutrient-poor lakes (Schindler and Novén 1971). Except for 1977, the species was monocyclic in Clearwater Lake (Fig. 1). Although the time and duration of the peak varied from year to year it never coincided with the time of maximum population densities of *C. vernalis*. In Cheat Lake, an acid mine drainage lake (pH 4.4) in the northern U.S.A., De Costa and Janicki (1978) observed that in the late summer and fall when planktonic crustacean biomass reached a maximum, it was comprised, as in Clearwater Lake, virtually entirely of

B. longirostris. In both lakes, the maximum biomass of *B. longirostris* was reached only after populations of the dominant predator, *M. edax* in Cheat Lake and *C. vernalis* in Clearwater Lake (Fig. 2) had declined. While acidification appears to be accompanied by a reduction in average zooplankton biomass, the Clearwater Lake data support the suggestion of De Costa and Janicki that copepod predation may have a profound affect on instantaneous herbivore biomass in acidic lakes as it does in non-acidic lakes (Kerfoot 1977).

Ice-free period, average biomass was not correlated with pH (or hydrogen ion activity)within the set of acidic lakes ($r = 0.04$, $\rho > 0.09$), nor for that matter within the set of non-acidic lakes ($r = 0.14$, $\rho > 0.6$). Zooplankton biomass was much lower in Hannah Lake than in the other acidic lakes (Table 3). Yan (1979) previously reported that among the same lakes phytoplankton biomass was also reduced in Hannah Lake. There was no correlation between the molar sum of Cu and Ni concentrations and zooplankton biomass when Hannah Lake data were excluded from the regression ($r = 0.11$, $\rho > 0.5$).

Excluding Hannah Lake data, zooplankton biomass in the acidic lakes was not correlated with pH ($r = 0.51$, $\rho > 0.1$). Although a rather large fraction of the variance in biomass could be attributed to phosphorus ($r = 0.62$, $\rho > 0.1$) or to total phytoplankton biomass ($r = 0.73$, $\rho > 0.05$), the coefficients of determination were not significant.

c. Food of herbivorous zooplankton in Clearwater Lake

The maximum size of particles ingested by filter-feeding cladocera is correlated with the size of the zooplankter (Burns 1968). Using Burns' empirical relationship ($y = 22x + 4.87$) between the diameter (y in µm) of the largest bead ingested, and carapace length (x in mm) of a filter-feeding cladoceran, one would predict that the maximum size of particle ingested by a *B. longirostris* of carapace length 0.26 mm (the average carapace length of *B. longirostris* in Clearwater Lake) would be 10.6 µm. Gliwicz (1969) found that although particles up to 14 µm in diameter were occasionally ingested, 85% of particles ingested by *B. longirostris* and *coregoni* were <5 µm in diameter.

From 1973 to 1978, dinoflagellates formed an average of 45% of the ice-free period phytoplankton biomass in Clearwater Lake (Yan 1979). Most (generally over 85%) of this was attributable to *Peridinium inconspicuum*.

The average diameter of *P. inconspicuum* was 14 μm (mean length of axes of 300 measured individuals). On two days (one in 1976 and one in 1977) on which *P. inconspicuum* formed almost all of the phytoplankton biomass, the guts of ten large (≈0.4 mm carapace length) *B. longirostris* were removed and the contents examined under compound microscopes. No *P. inconspicuum* were observed although identifiable algae were present in the gut contents. It is concluded that *P. inconspicuum*, although it is small for a *Peridinium*, is rarely ingested by *B. longirostris*. The dominant phytoplankter, comprising almost half of the phytoplankton biomass is most probably unavailable as an energy source to the dominant zooplankter of Clearwater Lake.

Of the 55% of the average phytoplankton biomass in Clearwater Lake not attributable to dinoflagellates, 80% on average was attributable to four taxa - *Oocystis sp.* (cells 5 μm in diameter, 8 μm in length), *Chlamydomonas sp.* (cells 3 μm in diameter, 6.5 μm in length), an unidentified Chrysomonad (cells 3 μm in diameter, 2.5 μm in length) and *Cryptomonas sp.* (cells 11 μm in diameter, 14 μm in length). Except for *Cryptomonas*, these genera are of a size that could readily be ingested by *B. longirostris*, although all phytoplankton that are ingested are certainly not assimilated (Porter, 1975). *Oocystis* was identified in the contents of the guts of the *B. longirostris* that were examined.

Although there is very little information on their densities in the limnetic zone of acidified lakes, it appears reasonable to suggest that densities of bacteria (Bick and Drews 1973, Guthrie et al. 1978) and detritus, which would normally form the bulk of material ingested by *B. longirostris* (Moore 1977), might be lower in acidic than in non-acidic lakes. If future work verifies this supposition, it would follow that zooplankton would have to rely more heavily on phytoplankton as an energy source. Among the phytoplankton species, herbivores would rely more heavily on the non-dinoflagellate than on the dinoflagellate component.

When the phytoplankton biomass of the acidic lakes was apportioned into dinoflagellate and non-dinoflagellate fractions, more of the variance in zooplankton biomass was indeed attributable to the latter ($r = 0.62$, $\rho > 0.1$) than to the former ($r = 0.10$, $\rho > 0.7$) fraction. The correlation with the latter fraction, while positive, was not significant. While acidification does result in a decrease in zooplankton biomass, this suggests that year-to-year variations in biomass are not readily predictable, although variations in the densities of cyclopoid predators or of ingestible phytoplankton may be important controllers.

d. Effect of zooplankton on phytoplankton community structure.

Hrbâcek <u>et al</u>. (1961) and Andersson <u>et al</u>. (1978) have demonstrated that zooplankton grazing can alter the composition of phytoplankton communities. If grazing losses of phytoplankton in acidic lakes were significant in comparison with the difference between phytoplankton renewal rates and losses attributable to other causes (mortality, sinking, advection) it could be hypothesized that the importance of the dinoflagellates in the acidic lakes might be a direct consequence of their size i.e. their inedibility. The acidic lakes in Scandinavia and Ontario are extremely clear, and have, in consequence, deeper euphotic and mixing depths than non-acidic lakes. Sinking losses of phytoplankton, expressed as the fraction removed $time^{-1}$, would in consequence, be proportionally less than in non-acidic lakes, and grazing pressures would have to be proportionally higher to alter the structure of phytoplankton communities.

The degree to which zooplankton communities influence phytoplankton communities is perhaps best assessed using <u>in situ</u> measurements of zooplankton filtering rates (Haney 1973), the filtering rate being that volume of water swept clear of prey by filtering-feeding zooplankton per unit time (Rigler 1961). Although filtering rates were not measured in this study, the zooplankton community of Clearwater Lake is extremely simple. In consequence, tentative estimates of filtering rates for the lake can be calculated with the following assumptions:

i. The zooplankton community is composed solely of *B. longirostris*. For the months of June to August this assumption would result in only a small underestimate of community grazing rates (Figure 1).

ii. The filtering rate is proportional only to herbivore body length and lake temperature (Burns 1969).

iii. Filtering rates are not pH-dependent. Although Ivanova (1969) observed that the filtering rates of *B. longirostris* varied with pH when organisms were transferred into vessels of different pH in the laboratory, Haney (1973) found that the filtering rates of *B. longirostris* measured <u>in situ</u> were very comparable in a non-acidic eutrophic lake (Heart Lake), an acidic (pH 4.5) dystrophic lake (Drowned Bog Lake) and a non-acidic, oligotrophic lake (Halls Lake) in Ontario.

iv. Empirical relationships between lake temperature, herbivore body length and filtering rates constructed for species of *Daphnia* are applicable to *B. longirostris*.

v. *B. longirostris* exhibits no diel variations in filtering rate. Filtering rates calculated by Haney (1973) for Halls Lake assumed no diel variations. Thus they are comparable to the herein calculated filtering rates for Clearwater Lake. Diel variations in filtering rates do, however, occur for cladocerans. Nocturnal filtering rates in *Daphnia* may be several times greater than diurnal filtering rates (Haney and Hall 1975, Starkweather 1975). The calculated filtration rates for Clearwater Lake may underestimate the actual diel filtration rates.

The morphometrically-weighted, average, annual ice-free period temperature of Clearwater Lake varied between 14.9 and 16.3^{o}C. Burns' relationship ($F = 0.153\ L_b^{2.16}$ at 15^{o}C) between filtering rate (F in ml animal^{-1} hr^{-1}) and body length (L_b in mm) was used to estimate the filtering rate of the Clearwater Lake zooplankton community. Using L_b = 0.26 mm, the filtering rate of an individual *B. longirostris* was calculated to be 0.2 ml animal^{-1} day^{-1}. Haney (1973) measured a filtering rate of 0.44 ml animal^{-1} day^{-1} for *B. longirostris* in Heart Lake. As Haney measured an average length of *B. longirostris* of 0.4-0.6 mm, larger filtering rates would be anticipated, and our calculated grazing rate in Clearwater Lake appears reasonable.

Calculated ice-free period average and single day maximum filtering rate for Clearwater Lake are shown in Table 5. The rates are extremely low because of the low density and small size of the herbivores. Haney (1973) calculated that the zooplankton of Halls Lake filtered an average of 4% of the lake's volume day^{-1}. The calculated average rates in Clearwater Lake are more than an order of magnitude less than in Halls Lake. Single day maximum grazing rates in Clearwater Lake never exceeded the mean grazing rates in Halls Lake (Table 5).

In acidic lakes that do not have associated metal problems, there is evidence to suggest that zooplankton standing stocks are low (Roff and Kwiatkowski 1977) and that larger herbivores (e.g. *Daphnia*) are replaced by smaller forms such as *Bosmina sp.* and *Diaptomus minutus* (Sprules 1975). This pattern is true also for Clearwater Lake, and we tentatively conclude that zooplankton filtering rates are lower in acidic than in non-acidic lakes.

Table 5: Average and maximum density of *B. longirostris* in Clearwater Lake and calculated average and maximum fraction of the whole lake volume filtered each day by *B. longirostris*.

		YEAR					
		1973	1974	1975	1976	1977	1978
Number of *B. longirostris* L^{-1}							
	Mean	6.0	6.7	5.1	9.1	17.2	6.9
	Maximum	20.6	62.4	21.9	28.2	54.1	25.6
% of whole lake volume filtered day^{-1}							
	Mean	0.12	0.33	0.10	0.18	0.34	0.14
	Maximum	0.41	1.3	0.44	0.56	1.1	0.51

The degree of control that zooplankton communities exert over the structure of phytoplankton communities increases as the ratio of zooplankton filtering rates to phytoplankton renewal rates increase. Dillon et al. (1979) and Almer et al. (1978) have recently suggested that rates of primary production are no lower in acidic than in non-acidic lakes of similar trophic status. As community filtering rates are so low in Clearwater Lake, and most likely in other acidic lakes we may hypothesize that zooplankton communities in acidic lakes exert very little control over the structure of phytoplankton communities and that the efficiency of energy transfer from primary to secondary trophic levels is lower in acidic than in non-acidic lakes.

A corollary of the first hypothesis is that the importance of dinoflagellates in acidic lakes is most probably not a consequence of the selective removal of smaller taxa by herbivores. It is most probably a manifestation of differences in tolerance among algal species to rapid decreases in (Yan and Stokes 1978) or to low pH.

These hypotheses, that the efficiency of energy transfer from primary to secondary trophic levels is reduced by acidification, and that changes in phytoplankton community structure that occur as lakes acidify are not related to grazing, are presented to provide directions for research. The data from which the hypotheses were derived are from Sudbury lakes that have been acidic and contaminated with Cu and Ni for many years. Hypotheses constructed to explain relationships in these lakes should be tested in lakes that have been recently acidified, have no associated Cu or Ni problems, or are at sufficiently early stages of acidification that lake pH's fluctuate markedly with time.

The testing of hypotheses similar to those presented in this report necessitates the collection of quantitative measures of seasonal and annual variations in the structure of entire zooplankton communities (protozoa, rotifera, crustacea and insecta). It also requires estimates of production at the level of the entire communities and of community interactions. These are laborious tasks, but with recent indications (Dillon et al. 1978) that a great number of Precambrian Shield lakes in Ontario may soon acidify, the need to understand changes in the dynamics of biotic communities in acid lakes is of paramount importance.

SUMMARY

Comparison of three years of net with three years of plastic trap data indicated that annual estimates of zooplankton community parameters from Clearwater Lake could be adequately derived from tow net collections.

Ninety percent of the samples taken in Clearwater Lake had between three and five species of crustacean zooplankton. This demonstrated that species richness in acidic lakes could be accurately estimated from a small number of samples. Unless Cu and Ni concentrations were as high as those of Hannah Lake, species richness was no lower than in acidic lakes without associated Cu or Ni contamination, although it was much less in non-acidic lakes. There were some differences, however, between species that were commonly dominant in the acidic Sudbury lakes and species commonly dominant in acidic lakes in Ontario that do not have associated heavy metal problems.

In the Haliburton lakes, the biomass of the zooplankton communities was 26-86 mg m^{-3} (annual average). Copepods contributed slightly more than cladocerans to the total. In Clearwater Lake, the biomass was much less (4-14 mg m^{-3}), and cladocerans were much more important contributors to total biomass than copepods (80-96%). *Bosmina longirostris* contributed >95% of the cladoceran biomass of the lake at all times.

In Hannah Lake, extremely low zooplankton biomasses were correlated with greatly elevated Cu and Ni concentrations. In the remaining acidic lakes, zooplankton biomass was not significantly correlated with pH, with Cu, Ni or TP concentrations, with total phytoplankton biomass or with that fraction of the phytoplankton (the non-dinoflagellates) presumed to be ingestible by filter-feeding cladocera.. It was concluded that year-to-year variations in zooplankton biomass in acidic lakes could not be readily predicted.

From published relationships between lake temperatures, herbivore size and herbivorous cladoceran filtering rates, it was calculated that the zooplankton of Clearwater Lake swept free of prey between 0.10 and 0.34% of the lake volume per day. This was more than an order of magnitude less than that of Halls Lake, a non-acidic, oligotrophic lake in central Ontario. As rates of primary production are apparently not reduced by acidification, it was hypothesized, that the dominance of the phytoplankton

community of acidic lakes by dinoflagellates, could be better explained by differences in pH-tolerance among phytoplankton species, than by selective removal of smaller, more edible taxa by zooplankton.

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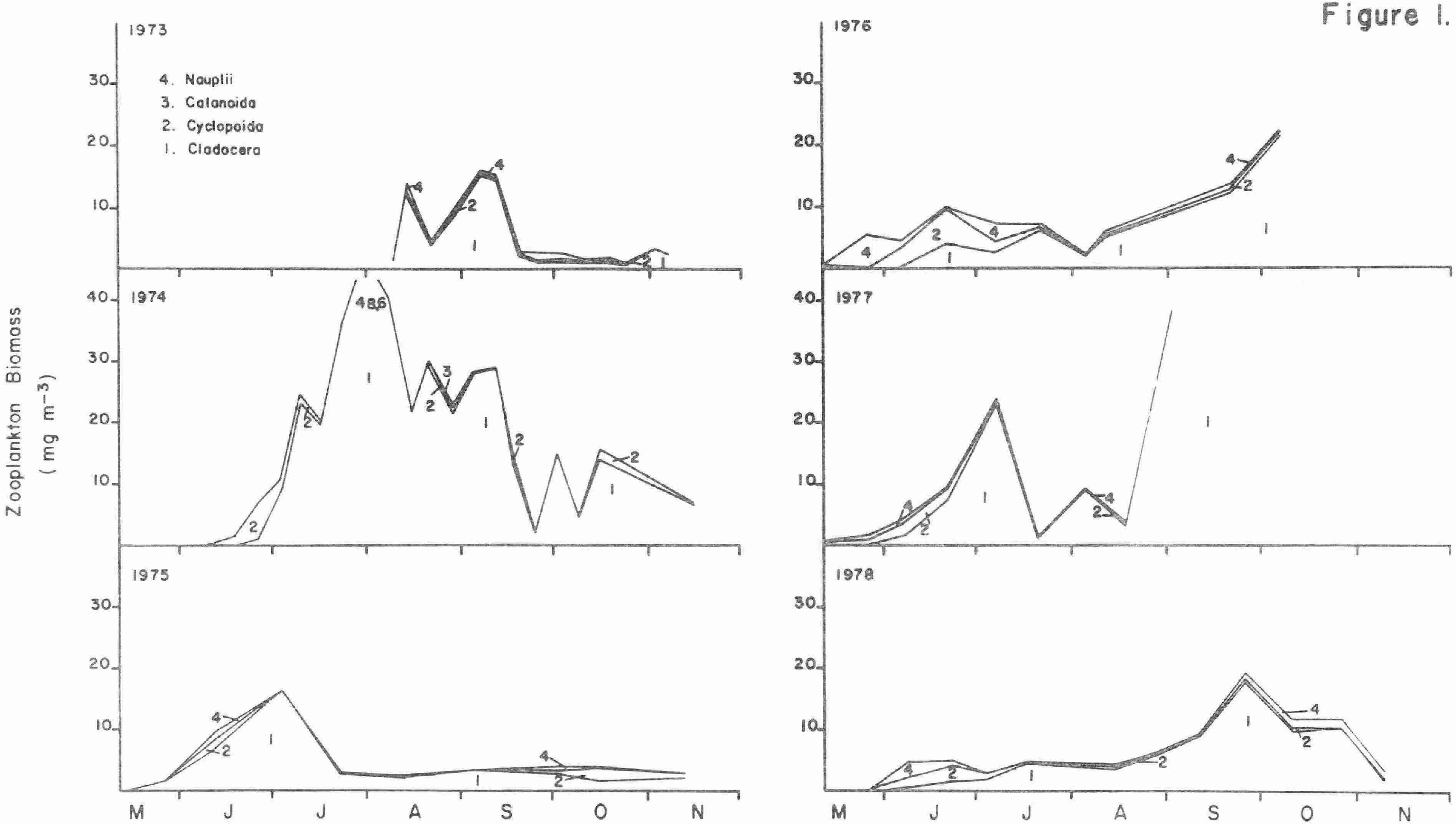
LIST OF FIGURES

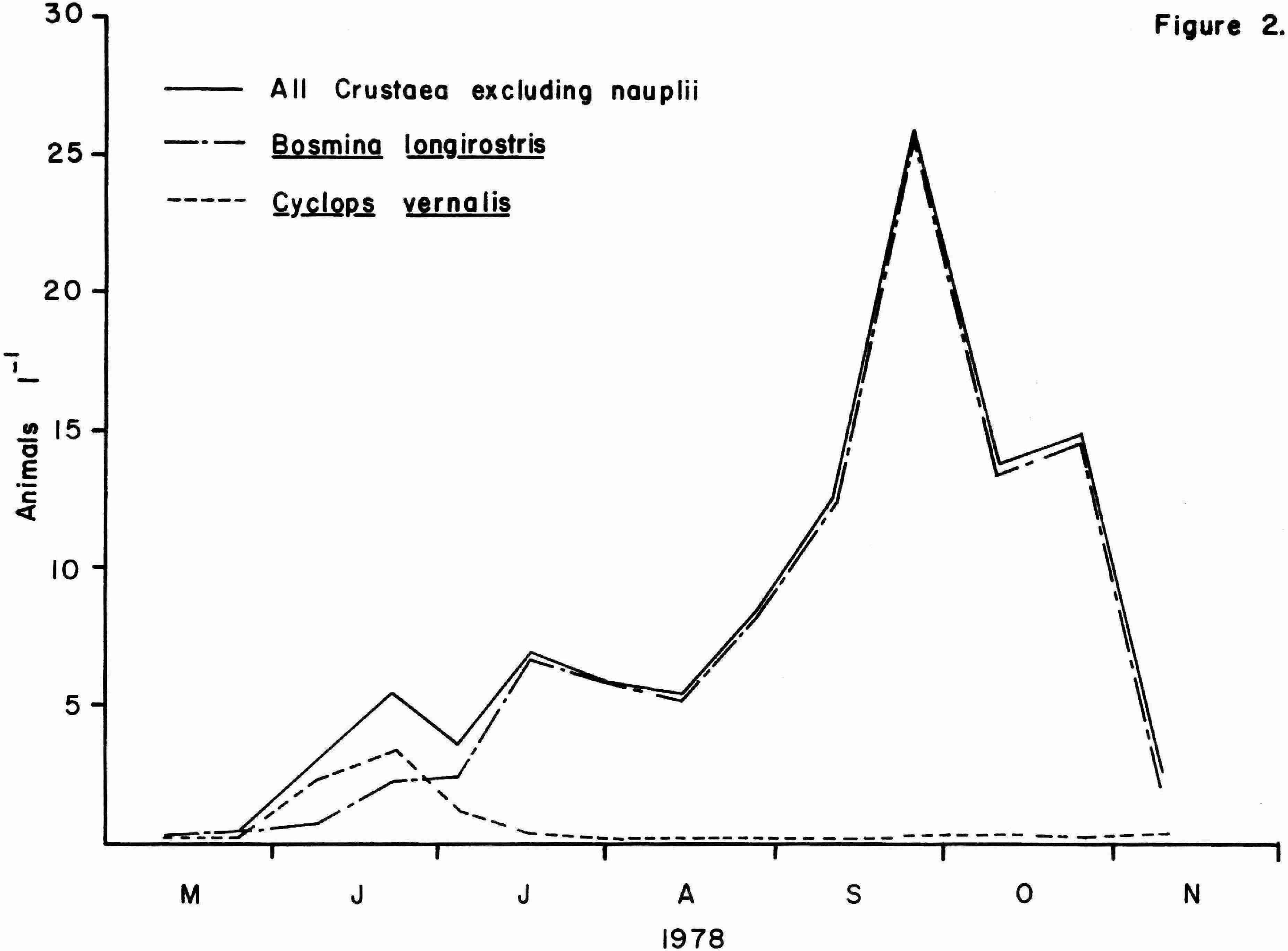
1. Cumulative biomass of planktonic crustacea of Clearwater Lake, 1973-1978.

2. Seasonal changes in the abundance of all crustacea (excluding nauplii), *B. longirostris* and *C. vernalis* in Clearwater Lake in 1978.



1973
1976
1974
1977
1975
1978
4. Nauplii
3. Calanoida
2. Cyclopoida
1. Cladocera
Zooplankton Biomass
(mg m-3)
48.6
M J J A S O N

Figure I.



30
25
20
15
10
5
Animals l^{-1}
All Crustaea excluding nauplii
Bosmina longirostris
Cyclops vernalis
M
J
J
A
S
O
N
1978

Figure 2.

ERRATUM

page 19, line 10, which reads
..."associated Cu or Ni contamination, although it was much less in non-acidic...

Change to

..."associated Cu or Ni contamination although it was much less <u>than</u> in non-acidic"...